π^--Nucleon Interactions at 4.5 Bev*

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An emulsion study has been made of π^--nucleon interactions at a pion energy of 4.5 Bev. The percentage of elastic scattering at this energy seems slightly smaller than at energies slightly above 1.0 Bev. One can deduce from this that the range of interaction between π^- and proton is greater than 1.0×10^{-13} cm.

The inelastic interactions resulting in two prongs have been considered in some detail. The angular distributions are suggestive of a direct knock out of a pion by the incoming pion. The momentum distributions obtained recently from diffusion chamber work at Berkeley also seem to support such a model. The four- and six-prong events are more complicated. The data from all inelastic interactions indicate the nucleons seem to go strongly in the backward direction in the c.m. system. Thus none of the interactions seem consistent with the statistical model of pion production.

I.

DURING the past several years there have been several surveys of π-p interactions in the Bev range.[1–4] The features of the collisions consists of a considerable elastic cross section which amounts to $\frac{1}{4}$ to $\frac{1}{2}$ of the total cross section. The differential elastic scattering curve has a characteristic diffraction appearance at small angles plus a tail extending to higher angles. The inelastic collisions in the region previously studied have consisted largely of the production of a single additional pion. The general features of these collisions can be understood by means of the isobar model of pion production.[5,6] There is not very much knowledge concerning the production of more than one pion.

II.

The data presented here are the result of on-track scanning in emulsion. We scanned plates exposed to the 4.5 Bev π beam at the bevatron. The plates came from a pellicle stack consisting of 23, 4 in.$\times$6 in.$\times$600 μ G-5 emulsions. There was a grid printed on each emulsion to facilitate tracing tracks. We have scanned in all about 1000 meters of track and found 128 collisions which were consistent with being π^--p collisions. Also we have found approximately 67 collisions which are consistent with being π^--n collisions. The criteria used in accepting collisions were very similar to those used in the 1.5-Bev work by Walker and Crussard.[1] The sample obtained must be comparable in purity to the 1.5-Bev work (i.e., one-half of the collisions are free and one-half are bound protons). Our scanning efficiency must be somewhat lower than in the 1.5-Bev work. This is presumably due to the very small average deflection of the pions in the collisions. We have a mean free path for a hydrogenic collision of about 7.4 meters as compared to about 5 meters at 1.5 Bev. An estimate of the scanning efficiency by comparing dip angle and plane angle distributions as originated by Clarke and Major[7] gives results which makes the mean free paths at 1.5 and 4.5 Bev comparable. Another estimate of our scanning efficiency can be made by comparing our mean free path for star production with that found by Clarke and Major.[7] These two estimates of the scanning efficiency give close to 75%. A breakdown of our results are given in Table I.

We feel it is necessary to make some corrections to these results. The elastic and other two prong interactions give rise to lightly ionizing products strongly peaked in the forward direction. Consequently the tendency to scan over these events is considerably greater than it is for the less collimated four-prong events. We would consequently attribute most of our 25% inefficiency to missing the two-prong events. The results after this correction are given in Table II in terms of cross section in millibarns for the various reactions. The total cross section taken in order to

TABLE I. Results of on track scanning.

Type reaction	No. cases
$\pi^-+p\rightarrow\pi^-+p$ (on free proton)	9
$\pi^-+p\rightarrow\pi^-+p$ (on bound proton)	9
$\pi^-+p\rightarrow$ no prongs	12
$\pi^-+p\rightarrow\pi^-+p+?$	34
$\pi^-+p\rightarrow\pi^++\pi^-+?$	31
$\pi^-+p\rightarrow$ 4 prongs	28
$\pi^-+p\rightarrow$ 6 prongs	5
$\pi^-+n\rightarrow\pi^-+?$[a]	29
$\pi^-+n\rightarrow2\pi^-+p+?$	16
$\pi^-+n\rightarrow$ 3 prongs (3 fast particles)	14
$\pi^-+n\rightarrow$ 5 prongs	8

[a] Deflections of greater than 5° with no other visible prongs.

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[1] W. D. Walker and J. Crussard, Phys. Rev. 98, 1416 (1955).
[2] Eisberg, Fowler, Lea, Shephard, Shutt, Thorndike, and Whittemore, Phys. Rev. 97, 797 (1955).
[3] Maenchen, Powell, Saphir, and Wright, Phys. Rev. 99, 1619 (1955).
[4] Walker, Hushfar, and Shephard, Phys. Rev. 104, 526 (1956).
[5] Crew, Hill, and Lavatelli, Phys. Rev. 106, 1051 (1957).
[6] S. J. Lindenbaum and R. M. Sternheimer, Phys. Rev. 106, 1107 (1957).
[7] J. O. Clarke and J. V. Major, Phil. Mag. 2, 37 (1957).

compute the cross section for the various reactions was 28.7 millibarns as measured at Berkeley by Wikner.[8]

We also include in Table II a comparison with Berkeley diffusion chamber data as recently reported by Maenchen.[9] We have corrected his data to correspond to the total cross-section measurement of Wikner[8] by using the charge-exchange cross section as measured in emulsion from this report. It is very likely that there is considerable scanning inefficiency in the diffusion chamber largely caused by missing the two-prong interactions. The correction of the diffusion chamber data has been made on this basis.

III. ELASTIC SCATTERING

We have estimated, on the basis of the number of elastic scatterings on free protons, a cross section for elastic scattering of 7.5 mb (with large uncertainties). The true value of the elastic cross section is probably bracketed by these various results. The most probable value in the author's opinion is the corrected diffusion-chamber value of 6 mb.

From the elastic scattering cross section one can make deductions about the range of interaction between the π's and protons. There are two means of doing this both of which involve using the optical model. One way is to compare the shape of the differential elastic-scattering cross section in the forward direction with that calculated for an opaque sphere, or a more sophisticated optical-model calculation. This method has several drawbacks. The main difficulties are that rather good statistics are required (at least the order of 1000 counts) and that bias free data at small angles are necessary. Neither this work nor that of Maenchen is very useful for this type of analysis. At an energy as high as 4.5 Bev the latter difficulty seems nearly insuperable.

The other method that can be used involves calculating R, the range of the interaction between the π and proton, from the total cross section on the basis of the absorption cross section and the ratio of the diffraction to the absorption cross section. This method has drawbacks also. If there is any real phase shift scattering then unless it can be separated it will give too much

TABLE II. Corrected results from emulsion and diffusion chamber work.

	Emulsion (corr.)	Diffusion chamber (corr.)
$\pi^-+p\rightarrow\pi^-+p$	4.5 mb	6.0 mb
$\pi^-+p\rightarrow$ neutrals	2 mb	
$\pi^-+p\rightarrow\pi^-+p+?$	8.5 mb	14 mb
$\pi^-+p\rightarrow\pi^++\pi^-+?$	8 mb	
$\pi^-+p\rightarrow$ 4 prongs	5 mb	6 mb
$\pi^-+p\rightarrow$ 6 prongs	1 mb	$\frac{1}{2}$ mb

[8] N. F. Wikner, University of California Radiation Laboratory Report UCRL-3659, January, 1957 (unpublished); also Bandtel, Bostick, Moyer, Wallace, and Wikner, Phys. Rev. **99**, 673 (1955).

[9] G. Maenchen, University of California Radiation Laboratory Report UCRL-3730, April, 1957 (unpublished).

TABLE III. Compilation of deduced ranges of interaction.

Energy	σ_d (in mb)	σ_A (in mb)	$R\times10^{-13}$ cm deduced from σ_d/σ_A	$R_{\text{shape}}\times10^{-13}$ cm
1.3 Bev	7.4±1.0[a]	19±2[d]	0.99±0.1	1.08±0.06[a]
1.4 Bev	7.0±1.0[b, c]	22±2	1.02±0.1	1.20±0.1[c]
4.5 Bev	6.0±1.5	22±2	1.08±0.15	0.90±0.15[e]

[a] See reference 10.
[b] See reference 1.
[c] See reference 2.
[d] See reference 11.
[e] See reference 9.

apparent diffraction scattering. We have taken the differential elastic scattering at 1.3 [10] and 1.5 [1,2] Bev and considered only the forward peak to be the diffraction scattering. The total cross sections used are those of Cool *et al.*[11] The results of the calculations from both methods are given in Table III.

The values of R below 1.0×10^{-13} are the most suspect of the lot. The best value is probably the one deduced by Leitner at 1.3 Bev.[10] It seems quite certain that the range of interaction between π and nucleon extends somewhat beyond 10^{-13} cm and is somewhat larger than the electromagnetic radius of the proton.[12] This seems very sensible if one attributes any size or structure to the pion itself.[13,14]

IV. INELASTIC PROCESSES

We have made studies of the inelastic processes at this energy. In using emulsion, one is rather limited as to the type of information that one can derive from the experiment. If the tracks are slightly above minimum it is often possible to identify the particle by means of tracing and grain count; we have identified numerous protons and a few π's and even fewer K's [four probable K's from π-p interactions]. It was not thought worthwhile to make scattering measurements on the apparently fast particles. Distortion and spurious scattering make such measurements of very dubious value. The

[10] J. Leitner, Ph.D. thesis, Columbia University, 1956 (unpublished).

[11] Cool, Piccioni, and Clark, Phys. Rev. **103**, 1082 (1956).

[12] E. E. Chambers and R. Hofstadter, Phys. Rev. **103**, 1454 (1956).

[13] Recently Feinberg and Pomerancuk[14] have made the observation that occasionally, at least, one would expect the diffraction scattering to result in an inelastic process. Such a process would be analogous to the electromagnetic emission of a photon in the course of an otherwise elastic scattering of two charged particles. According to these authors one would expect the fast pion to have an angular distribution very similar to the elastically scattered pions, that is a diffraction peak in the forward direction. Experimentally it is difficult or impossible to distinguish such a process from a *bona fide* inelastic collision. One would expect the excitation to be small. We would expect then the π^+ to be strongly correlated with the nucleon in direction, which would mean that one would find the π^+ to be slow in the lab system. There do not seem to be many π^+ productions of this type. The effect is probably less than one millibarn in cross section which should not affect our conclusions concerning the ratio of diffraction-to-inelastic scattering very much.

[14] E. L. Feinberg and I. Pomerancuk, Suppl. Nuovo cimento **4**, 652 (1956); see also A. I. Akhieser and A. G. Sitenko, Phys. Rev. **106**, 1236 (1957).

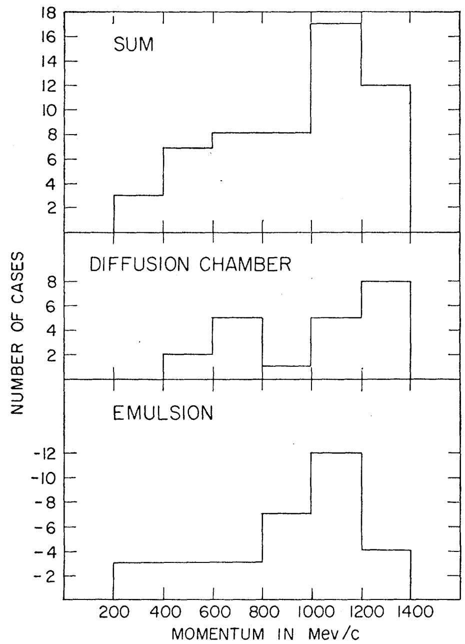

FIG. 1. Center-of-mass momentum distribution of protons from two-prong cases. These results are taken from the emulsion work and the diffusion chamber results of Maenchen.[9]

two-prong interactions will be discussed first. In approximately one-half of these a proton was identified. This is quite consistent with the diffusion chamber results of Maenchen. Figure 1 shows the center-of-mass momentum distribution of the identified protons. The maximum possible momentum of the proton in the center-of-mass system is 1.4 Bev/c. Also in Fig. 1 is the histogram taken from the cases of identified protons from the two-prong cases found in the diffusion chamber work by Maenchen. There may be some discrepancy between the two methods because of a tendency to classify some of the cases in emulsion as "edge" elastic collisions. That is an elastic collision with a bound proton. The identification is most difficult when the proton from the inelastic scattering has a high momentum in the center-of-mass system. From a comparison of the momentum spectrum of the protons from the four-prong cases, probably most of the cases in which the momentum of the proton is less than 1 Bev/c are examples of multiple meson production (two or more π's produced). There are roughly equal numbers of cases in which the proton has momentum of less than or greater than 1 Bev/c.

The three-prong events, which must be roughly comparable reactions with a neutron, seem to show a ratio of more than 2:1 for the number of reactions $\pi^- + n \rightarrow (3\pi + n + ?)$ and $(2\pi + p + ?)$ to reactions of the type $\pi^- + n \rightarrow 2\pi^- + p$. The best estimate is that the order of $\frac{1}{2}$ to $\frac{1}{4}$ of the inelastic two-prong cases are single pion production.

The angular distribution of the various products are shown in Fig. 2. The general feature shown is that the nucleons have a very strong tendency to continue to move in their original direction and likewise for the π^-. For the reactions which seem to be of the type $\pi^- + p \rightarrow \pi^+ + \pi^- + n + ?$ the π^+ and π^- seem to show features similar to the π^- from the reactions $\pi^- + p \rightarrow \pi^- + p + ?$ in that there seem to be relatively few π's in the backward hemisphere. We wish to consider primarily single-pion production and consequently consider the momentum distribution of the pions going strongly forward and the nucleons going strongly backward in Fig. 3. These data have been extracted from the results of Maenchen.[9] The single-pion pro-

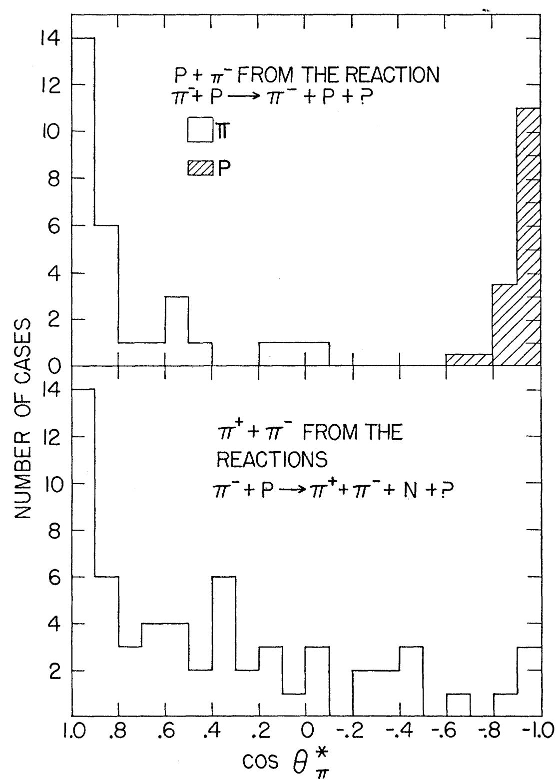

FIG. 2. Angular distribution of protons and π's from from two-prong interactions.

duction cases probably usually occur as a result of high-impact-parameter collisions and as a result one would expect the products to go forward and backward in the center-of-mass system. From these data one can make qualitative deductions concerning the high-impact-parameter collisions. One thing that seem fairly certain is that the isobar model does not seem to be very relevant at this energy. If the incoming pion excited the nucleon into a $\frac{3}{2}$-$\frac{3}{2}$ state, then the π would lose of the order of 130 Mev/c of its original momentum. The secondary pions would be fairly closely correlated with the nucleon and would produce a broad spectrum extending from about 100 to 650 Mev/c. Thus the π spectrum should be something like a line at 1270 Mev/c

and a flat spectrum reaching from 100 to 650 Mev/c. There appear to be relatively few cases consistent with such a picture. The nucleons should show a flat spectrum extending from 700 to 1300 Mev/c, and again the data are not grossly consistent with such a picture. Figure 4 shows the distribution of angles between the two pions from the two-pion cases from the emulsion work. According to the isobar picture the average angle should be something the order of 140°, which is definitely inconsistent with the data. The data, needless to say, are not consistent with the statistical model because of the asymmetry in the angular distribution of the nucleons.

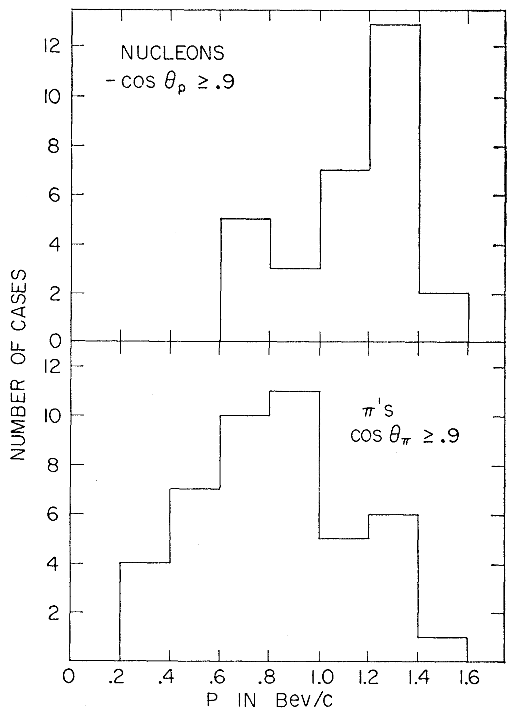

FIG. 3. Momentum distribution of π's from two prong interactions which are strongly collimated in the forward direction, $\cos\theta_\pi \geqslant 0.9$. Momentum distribution of nucleons going strongly in the backward direction, $-\cos\theta_N \geqslant 0.9$. These data have been extracted from the work of Maenchen.[9]

The simplest picture that would seem consistent with these results is that of a simple knock-out process in which the incoming pion materializes one of the pions out of the field of the nucleon. One can think of this as a pion-pion collision in which the virtual pion is knocked out of the nucleons proper field. Such a model was proposed by Dyson and Takeda to explain the bump in the π^--p cross section at 1.0 Bev. Such a model has the following qualitative features.

(1) The primary and secondary pion will tend to have equal momenta (approximately one-half the momenta of the primary pion). Thus the pion spectrum should be peaked at about 700 Mev/c in the c.m. system and

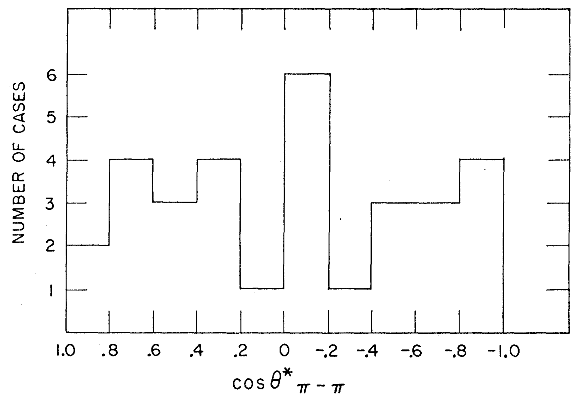

FIG. 4. Distribution of angles between π's from two-prong interactions.

should be rather flat although such details depend on the angular distribution in the π-π c.m. system.

(2) The nucleon will tend to maintain its original direction in the c.m. system. If the virtual π is at rest at the instant of collision the nucleon will have a momentum of about 1.2 Bev/c.

(3) The average angle between the two π's in the π-p c.m. system will be slightly more than 90°. The average angle in the lab system will be about 27°. These are again calculated on the assumption that the collided π was at rest previous to the collision so that the most probable angle is about $\theta \approx 2/\gamma_\pi$, where γ_π is the γ of the π-π center-of-mass system.

The qualitative difference between this model and the isobar model are very extreme. The knock-out model

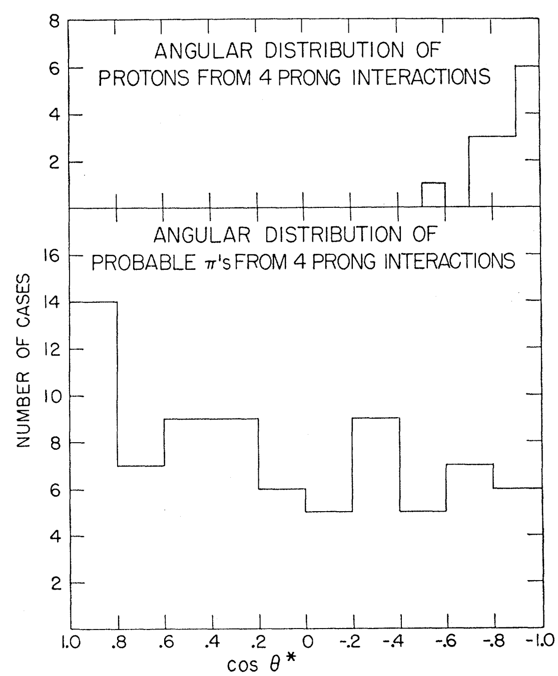

FIG. 5. Angular distribution of products from the four-prong interactions.

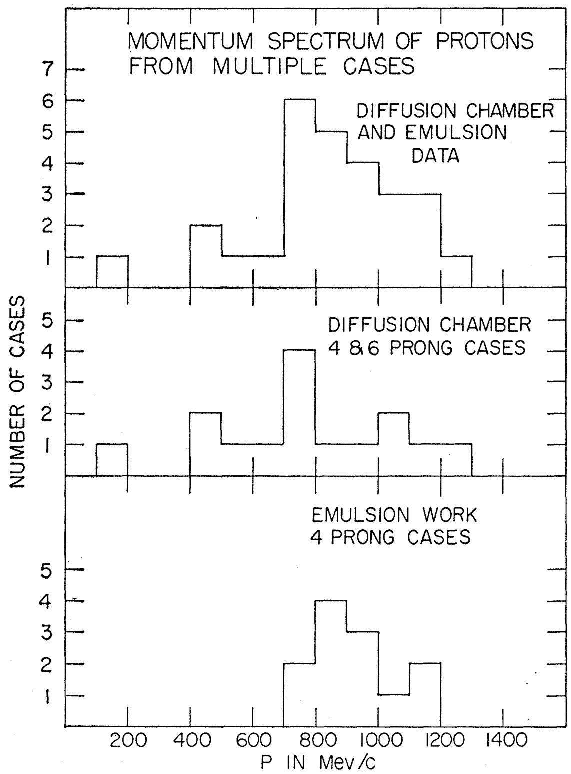

FIG. 6. Center-of-mass momentum distribution of protons from the four-prong interactions. The diffusion chamber data were taken from the work of Maenchen.[9]

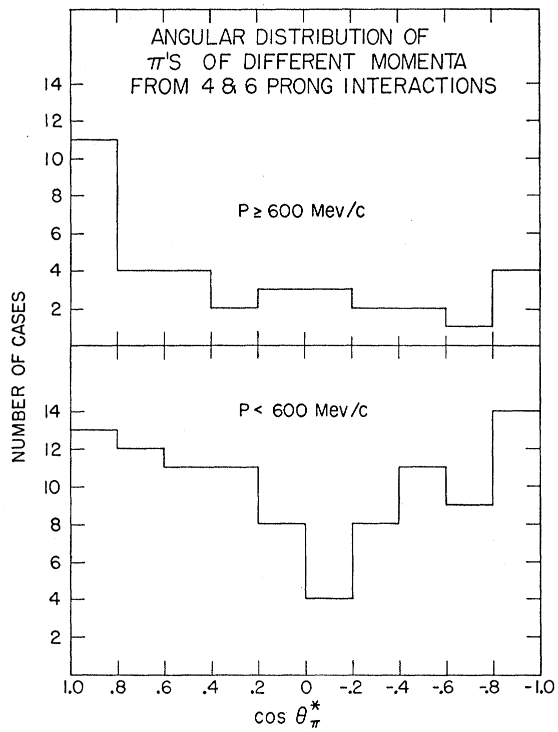

FIG. 7. Center-of-mass angular distribution of π's from 4- and 6-prong interactions according to whether the momentum of the π is greater or less than 600 Mev/c. These data were extracted from the work of Maenchen.[9]

seems to have qualitative features that are consistent with the present data. Although we are obviously unable to separate the single from the multiple pion production cases, although this may not be a drawback.

Several (6) of the π-n collisions seem particularly indicative of such a picture. The proton is found with angle and momentum consistent with an elastic collision except there are two pions instead of one close to the elastic angle for the π.

The multiple pion production cases are very difficult to analyze and systematize. Figure 5 shows the angular distribution of the light tracks and identified protons from the 4-prong interactions. The angular distribution of the light tracks from the five- and six-prong interactions seem to be essentially isotropically distributed in the center-of-mass system.

The general feature of these interactions is that the nucleons seem to go into the backward hemisphere and that the π's are nearly isotropically distributed. The angular distribution of the protons seems to be broader and their momenta lower than the protons from the two-prong interactions. Figure 6 shows the momentum distribution taken from the emulsion work and diffusion chamber work. The light tracks seem to show a slight peaking in the forward direction in the c.m. system which might indicate the presence of the degraded primary. It should be pointed out that we have undoubtedly made some mistakes in identification and angle transformation and put some particles that had low velocities in the center-of-mass system into the forward direction.

Figure 7 was extracted from the work of Maenchen showing that the π's of momentum greater than 600 Mev/c tend to go forward and the rest are distributed more or less isotropically in the c.m. system. This result supports the result that the nucleons go backward in the c.m. system.

Again it is very difficult to understand these results on the basis of the statistical model because of the asymmetry of the protons. However, any identified protons are necessarily in the backward hemisphere. We identified protons in 50% of our 4-prong cases. One expects a considerable amount of 3π as well as 2π production and consequently a considerable number of neutrons produced so that it does not seem likely that we have simply called $\frac{1}{2}$ of the protons pions. Our results are consistent with the diffusion chamber results. The nucleon on the average goes into the backward hemisphere and high-energy pion into the forward hemisphere. The low-energy pions seem to be distributed more or less isotropically. This sort of result does not seem to be consistent with any isobar type model either. Since the nucleons seem to go into the backward hemisphere the parent excited nucleon must have been going into the backward hemisphere. When the excited state decays it should carry a large fraction of its progeny with it into the backward hemisphere. As pointed out above, however, the low-energy pions are more or less isotropically distributed in the π-p center-of-mass system.

The π-π collision type model could presumably account for some of the observed features in multiple production.

These collisions seem to show a considerable larger momentum change on the part of the nucleon. This makes it likely that they are collisions which involve on the average smaller impact parameters. The features of the pion-pion collision would be more thoroughly lost in such a collision because of the more rapid motion of the target pion. The difficult things to account for are the backward motion of the nucleons in conjunction with the near isotropy of the low-energy pions. The near isotropy might be accounted for by a combination of effects such as direct ejection of pions plus some post-collision emission of pions by the nucleon along the lines of the excited-nucleon model.

DISCUSSION

The results at 4.5 Bev in some respects seem fairly coherent with those at the lower energy. The total cross sections and absorption cross sections seem to be constant in the range from 1.5 to 4.5 Bev.[8,11] The resultant picture is that the nucleon seems to present a fairly large ($\sim 1.1\times 10^{-13}$ cm) and transparent target to the incoming pion. As the author has pointed out previously,[4] the pion-pion interaction model can account for some of the general features of the cross section and range of the π-nucleon interaction. At this energy perhaps 7 or 8 mb of the cross section can perhaps be accounted for as a direct knock-out process in which a pion is ejected directly from the field of the nucleon. The more multiple processes are more complicated and from the limited amount of data no very clear physical picture arises. The Fermi statistical model at least as originally proposed by Fermi does not seem to be a possible mechanism. It is possible that some variation of the Fermi model such as that proposed by Bhabha[15] may account for some of the features observed in these multiple processes. The bremsstrahlung type process of the Lewis-Oppenheimer-Wouthuysen theory[16] does not seem to be able to account for the qualitative features observed. A model involving the pion-pion interaction seems to come closer than any of the others to giving qualitative features similar to those observed for the multiple processes.

ACKNOWLEDGMENTS

The author wishes to acknowledge several helpful conversations with Professor H. W. Lewis. Also the author wishes to thank Mrs. L. Maloney for her work in scanning the plates. The exposure at the Bevatron was carried out with the aid of Dr. E. J. Lofgren.

[15] H. J. Bhabha, Proceedings of the International Conference on Theoretical Physics, Kyoto and Tokyo, 1953 (Science Council of Japan, Tokyo, 1954), p. 143.

[16] H. W. Lewis, Revs. Modern Phys. 24, 241 (1952).